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The interaction between highly automated driving and the development of drowsiness

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Abstract

The progress in developing highly automated driving applications and the corresponding opportunities for the driver to take himself out of the loop have raised a couple of questions regarding the effects of highly automated driving on the driver's state. Within this framework a simulator study was conducted at the Würzburg Institute for Traffic Sciences (WIVW GmbH) in collaboration with Volkswagen Group Research with 16 test drivers. The drivers took part in three sessions each requiring him/her to drive on a highway with a speed limit of 120 km/h. Drowsiness was assessed continuously during the drive by eye lid closure measurements and was classified into 4 different levels. Whenever a driver reached a certain drowsiness level during the manual drive, a test phase of 15 minutes was initiated ending with a take-over scenario. Depending on the experimental condition, the test phase was 1) driving with a highly automated system (lateral and longitudinal control was performed by the automated system allowing hands-off driving), 2) driving with the system and additionally performing a quiz task or 3) driving manually during the test phase. The results show that especially in the manual and the highly automated condition without secondary task engagement the drowsiness level clearly increased during the 15 minutes test phases. During the phases with highly automated system active and the additional quiz task, drowsiness stayed on a low level and remained constant during the test phase. This implicates that an interesting and motivating secondary task has the potential to raise driver's alertness significantly, especially during highly automated driving.

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1. Introduction

1.1. Effects of highly automated driving on the driver's state

The progress in developing highly automated driving applications and the corresponding opportunities for the driver to take himself out of the loop have raised a couple of questions regarding the effects of highly automated driving on the driver's state. Systems classified into automation level 2 (according to SAE definitions) take over continuous lateral and longitudinal control tasks from the driver. However, he is still in responsibility for monitoring the driving environment as a number of system limits require his/her ability to be able to immediately take-over the driving task. Therefore, the driver's role changes from an active operator into the one of a passive observer. The consequence might be a decreased attentional focus towards the driving task ([1], [2]), decrements in driving performance (e.g. [3]) and changes in driver's arousal level (e.g. [4], [5], [6]). Subjective statements from drivers indicate that they are aware of the risks of getting drowsy when driving with highly automated systems ([7]).

In parallel, the drivers' wish to activate or stimulate themselves increases, e.g. by interacting with non-driving related tasks during highly automated driving (see [8], [9]). Also the actual engagement in such tasks raises in highly automated drives (e.g. [10], [11]). Though, driver's awareness on the potential risks being too highly distracted increases as well ([11]).

This problem gets less pronounced in the next years if SAE level 3 systems will be developed. By the improvement of sensors, situations that still require a take-over by the driver can be anticipated much earlier. Thus, the time window until the driver has to be back in the loop is more comfortable. Therefore, the driver is no longer requested to continuously monitor the driving environment and is explicitly allowed to direct his/her attention to defined non-driving related tasks, such as email correspondence or surfing the internet. However, the driver might not be allowed to fall asleep as he maintains the fallback level of the system.

The effects of such systems requiring no more monitoring are rarely studied so far. What can be assumed is that the risk of system misuse will increase (e.g. using the system in order to sleep; [12]).

1.2. Countermeasures against drowsiness in highly automated driving

Neubauer et al. [13] state that two different types of fatigue have to be distinguished in order to understand the specific effects of automation. While passive fatigue, which mainly results from monotony and underload conditions, will even be promoted by automation, active fatigue in the sense of exhaustion and stress by too high workload can be potentially reduced by automation. But [13] could not prove their hypothesis that if drivers could freely choose to activate the automation during a 30-minutes manual drive for 5 minutes this would have a positive effect on the subjectively perceived drowsiness. Their study results implicated that using automation as countermeasure against drowsiness would not be effective. A study within the EU project HAVEit ([11]) showed that a transition from highly automated driving level back to manual driving would only have short-term positive effects on driver's drowsiness level. Reducing the automation level therefore was not able to stop the proceeding development of drowsiness over time.

1.3. Effectiveness of secondary tasks as countermeasures against drowsiness

When talking about non-driving related tasks very often only the negative distraction effects of these tasks are discussed. When driving with automated systems classified on SAE level 3 the driver will explicitly be allowed to take him/herself out of the loop and to direct his/her attention to defined non-driving related tasks. Possibly this opportunity to interact with additional activities could counteract the potential negative effects of the automation by reducing monotony and increasing the driver's arousal. In the literature there are several hints that specific secondary tasks can increase driver's vigilance and intensify task engagement (e.g. [14], [15], [16], [17]). However, these statements actually refer only to manual driving conditions and driver's state is mostly assessed by using subjective measures.

2. Research question

The following simulator study, which was held in cooperation with Volkswagen Group Research, studied the effects of highly automated driving on driver drowsiness while doing nothing compared to while performing a non-driving related additional task, here a quiz task. As reference, the effects of continuing driving manually were assessed. In contrast to existing studies driver's drowsiness level was assessed objectively and online during the test drive using an algorithm based on eye lid closure measurement ([18]) classifying the driver's drowsiness on 4 levels (awake, hypovigilant, drowsy, sleepy).

3. Methodology

3.1. State dependent experimental plan

As the development of drowsiness is a process that is inter- and intra-individually highly variable, it was decided to use a state dependent experimental plan. I.e. a certain intervention (here: the activation of the highly automated system) was dependent from the drowsiness development of each driver. The basic idea is to use manual driving phases in order to bring the driver on a certain drowsiness level (called "waiting phases"). The duration of these phases was variable. As soon as a certain level was reached a so called "test phase" with a fixed time interval of 15 minutes followed which ended up in a take-over scenario. Depending on the experimental condition, the test phase was either

- 1) driving with a highly automated system (HA)
- 2) driving with a HA system and additionally performing a quiz task (HA+QT)
- 3) driving manually during the test phase (MAN)

The time interval of 15 minutes was defined according to results from prior studies on the expected effectiveness of secondary task activation (see [11], [16]). After the take-over scenario the driver proceeded driving manually until he/she reached the next higher drowsiness level which again triggered the 15 minutes test phase and so on. Optimally, this sequence was repeated 3 times according to the 4 assumed drowsiness levels: In an alert state (this state was assumed after a fixed time interval of a 10 minutes baseline drive), on a hypovigilant level, on a drowsy level and finally on a sleepy level. The experiment was finished if the driver had reached the highest drowsiness level or if the defined maximum time for the drive (2.5h) was reached.

3.2. Study sample

Sixteen test drivers took part in the study. All of them were recruited from the test driver panel of the Wuerzburg Institute for Traffic Sciences (WIVW GmbH) and therefore had participated in an extensive simulator training program (minimum 2.5 hours). Mean age of drivers was 30.5 years with a standard deviation of 7.4 years. On average, drivers drove 13250 km per year. Experience with assistance system of the sample was low. However, most of the drivers had already gained experience with ACC systems or even highly automated hands-free systems from other simulator studies at the WIVW. Each driver participated in three experimental sessions, which started either at 6 o'clock a.m. or 2.30 p.m. 8 drivers selected the morning date, 7 the date in the afternoon. The drivers were instructed not go to bed before 12 p.m. the night before the experimental days. The afternoon group was additionally requested to get up at 6 in the morning. On average, drivers of the afternoon group had slept 5h, drivers of the morning group 4h40min. On the experimental days drivers should refrain from consuming coffee, tea, energy drinks, alcohol and drugs. Between the experimental days at least one recreation day was considered.

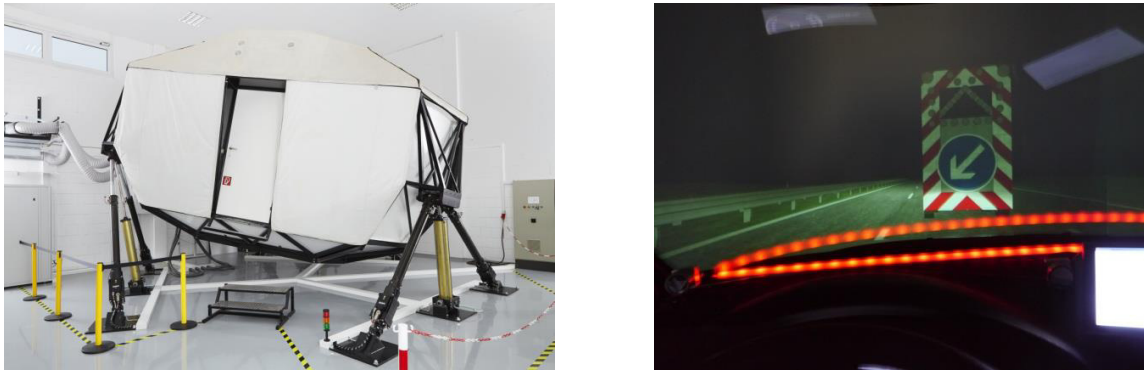


Fig. 1. a) The WIVW driving simulator, b) the take-over scenario.

3.3. Simulator and test course

The study was conducted in the WIVW driving simulator with motion system (see figure 1a); for more information see www.wivw.de). The drivers drove on the middle lane of a three-lane motorway with slight curvature and a recommended speed of 120 kph. There was little traffic on the opposite lanes. Every kilometer a truck had to be passed. On the left lane vehicles passed in longer time spans. Except of the first 10 minutes (the baseline drive) the drive was realized in nighttime lighting conditions with headlights being switched on. The first baseline section was used as a reference for evaluation of the eye lid closure parameters. This section was 20 km and lasted 10 minutes. It was conducted in daylight and the drivers were explicitly instructed to drive very attentive. After this section the first test phase immediately followed.

The waiting phases which served to reach the next higher drowsiness levels were composed of 6 single sections of 2km which could be driven through in an endless loop. As soon as the threshold for the next higher level was detected by the drowsiness algorithm, the test phase of 15 minutes was triggered automatically by the driving simulation (not later than after 1 minute).

The test phase itself was 33km long and was comparable to the waiting phase with regard to curvature and traffic density. After 30km (respectively 15 minutes) in the sessions where the HA system was active, a take-over request (TOR) was given. 400m later, respectively 12s later, a moving construction site was positioned on the middle lane (see figure 2b) meaning a site vehicle with a direction sign to the left. It was assured that no other vehicle passed from behind at this moment. After the take-over scenario a 2 km section had to be driven manually until the driver got in the next waiting phase. In order to minimize learning effects during the test drive this scenario had been practiced four times before the actual start of the test drive.

3.4. Automated system and HMI

For the study, a simplified highly automated (HA) system of WIVW was used which takes over lateral and longitudinal control from the driver (comparable to a combination of an adaptive cruise control system and a lane-centered lane keeping assistance system) and allows hands-free driving. The target speed was fixed to 120 km/h. The HMI of the system, defined together with Volkswagen Group Research, consisted of a visual graphical user interface (GUI) displaying the system status in the instrument cluster and LED lights in the windshield. Transitions between system states were additionally announced by acoustic signals.

During the waiting phases the system was set in an off-state, and could not be activated. With entering a test phase in the two experimental sessions HA and HA+QT the system was made “available” and the driver should activate it by pressing a button at the steering wheel. The test phases should then be driven with system active. 12 s before reaching the construction site the take-over request was triggered. The driver was explicitly instructed to deactivate the system by button press as soon as he/she felt ready for taking over the driving task again and then to

pass the construction site by him/herself. The functionality of the system could be tested in a 10 minutes practice drive prior to the test drive.

3.5. Quiz task

In the experimental session HA+QT (highly automated + quiz task) the drivers should interact with a non-driving related activity during the test phases while the HA system was active. Here a quiz task was selected according to the wide-known TV-gameshow “who wants to be a millionaire”. Here the correct answer to a question has to be selected out of a number of given options. It is assumed that such a task requires high task involvement and might have an activating effect. The questions were presented visually on a touch screen which is located on the center console. The driver had to select the correct answer by touching the respective options A), B) or C). The driver got feedback about the total number of answered questions and the number of correct answers. He/she was instructed to continuously and intensively interact with the task as long as it was presented. The task should be started by the driver as soon as the HA system had been activated and should be performed continuously and with high attention. The test leader paused the task after a take-over scenario and the driver restarted it in the next test phase. The drivers had the chance to practice the task prior to the test drive.

3.6. Online assessment of drowsiness during the drive

The driver's state was assessed by using the drowsiness detection algorithm from Hargutt [18]. His drowsiness index is based upon the analysis of eye-lid movements. They are measured via copper coils fixed at the upper and lower eye-lid of a driver. The algorithm for detecting drowsiness is a combination of several parameters which are controlled by different psychological processes and are sensitive to different energetic states: blinking duration, blinking frequency and eyelid opening level. These three parameters are combined in a hierarchical evaluation process. It appears that increased blinking frequency is the earliest eyelid indicator of impaired vigilance, which identifies level 2 (level 1 would be alert). Prolonged blinks in addition identify level 3 (drowsy). Level 4 is defined by small eyelid opening level in addition (or microsleep or very long closures; sleepy). There is a significant correlation between the fatigue index, the amount of alpha activity in the EEG, the number of missing in a vigilance task and the tracking ability of a driver ([18]). Due to the high interindividual variability of these parameters a baseline measurement assuming an alert driver is necessary which can then be used as reference to infer that a person has got drowsy.

In order to online assess the drowsiness level of a driver each single blinking event is first classified into state 0, 1, 2 or 3. After that a moving average of the last 15 blinking events is calculated so that a continuous drowsiness index evolves. The following thresholds were chosen to define the 4 drowsiness categories/levels:

- Level 1: state reached after the 10 minutes baseline-drive
- Level 2: drowsiness index between 0.9 and 1.5
- Level 3: drowsiness index between 1.5 and 2.1
- Level 4: drowsiness index > 2.1

It has to be noted that level 1 is not equal to an alert level but was defined as the state reached after the 10 minutes baseline drive. The analyses showed that due to sleep deprivation most drivers were already somewhat hypovigilant at this time.

4. Results

4.1. Individual drowsiness development of the drivers

In general it has to be noted, that according to the expectations, the evolution of drowsiness showed high variation between the drivers. Therefore, the four drowsiness levels were not run through in all the drives. It happened on the one hand that levels in between were skipped (either only level 2 or level 3 or even both level 2 and 3 together) and that drivers directly jumped to a higher level. This is an indicator that drowsiness evolved very fast. This happened more often in the MAN condition. On the other hand, in some other drives the session was stopped after reaching level 3 (in one case even after level 2) as it could be foreseen that drivers would not become even drowsier. Interestingly, this was strikingly frequent the case in HA drives without the secondary task. One explanation for this can be found in the online protocols that were recorded during each drive: Some drivers in the HA conditions in fact had the eyes closed for longer time periods from several seconds up to a few minutes. They seemed to use the phases with HA system active for sleeping or at least taking a rest. Therefore they were that refreshed in the following manual driving phases that the prolongation of drowsiness development was delayed, at least until the duration of the study session.

4.2. Drowsiness development during the test phases

For describing the drowsiness development over the test phases the drowsiness index was recalculated as mean value for every 5km of the test phase (2.5 minutes intervals). Please note that this index, calculated offline cannot directly be compared with the one that emerged from the online algorithm using a moving average calculation. From figure 2a) different trends can be seen dependent from the driving condition and the drowsiness level. No statistical

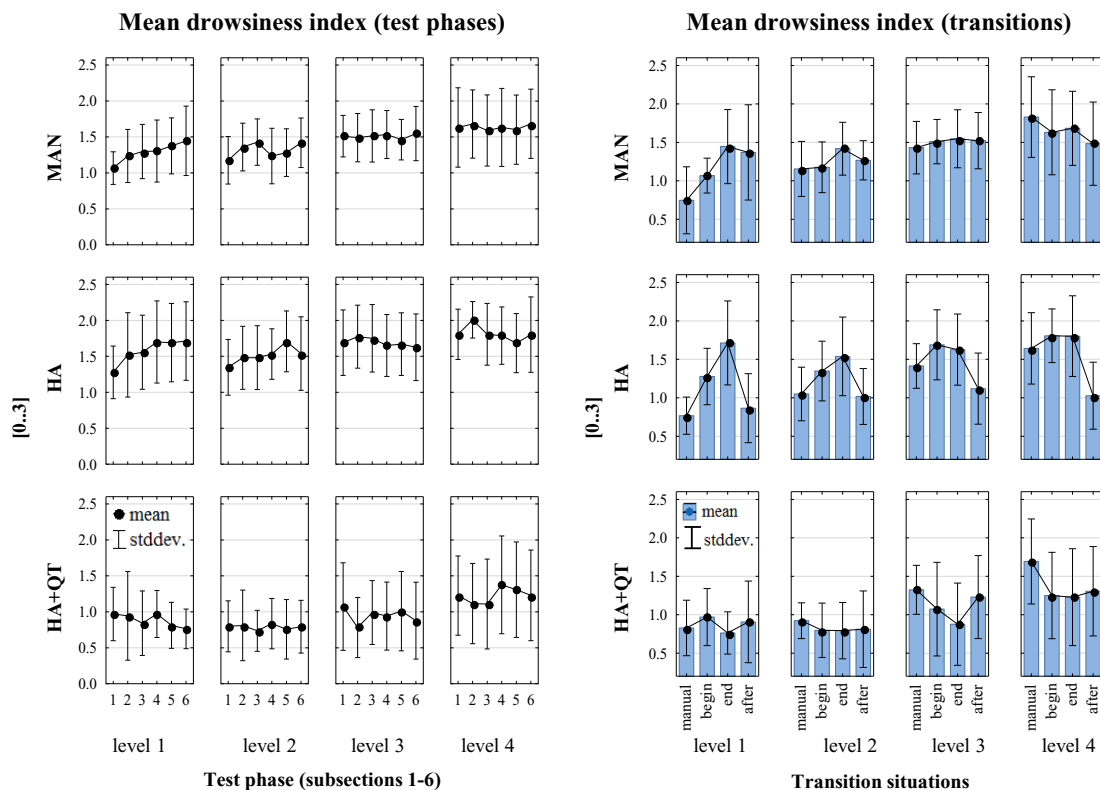


Fig. 2. a) Mean drowsiness index during the test phases (across the six subsections of 2.5min duration) and b) at the transitions into the test phases and out of the test phases, both dependent from driving condition and drowsiness level.

tests had been conducted due to the varying number of valid cases per cell.

Both in the MAN condition and in the HA condition an increase in drowsiness across the 6 subsections can be observed. This effect is more pronounced for the lower drowsiness levels compared to level 3 and 4. This can be attributed to a kind of ceiling effect in the way that if drowsiness level is already very high it is physiologically very unlikely that it rises even further. In contrast, when driving in the HA+QT condition a very low drowsiness level (drowsiness index of about 1) can be kept stable at least throughout the 15 minutes lasting test phase. This effect seems to be independent of the initial drowsiness state.

4.3. Effect of the transition into the highly automated mode and out of it

For analyzing the immediate effects of activating the HA system a comparison is made for the last section in the waiting phase compared to the first section in the test phase (when system had just been activated, compare “manual” vs. “begin” in figure 2b).

In the MAN condition there seems to be no obvious change in drowsiness beside the general time-on-task effect and a slight increase in state 1 from the end of the waiting phase to the start of the test phase. However, this is probably explainable by the relatively fast transition from the alert state to the hypovigilant state.

As expected, the highest increase of the drowsiness index can be seen if the HA system is activated without any opportunity to interact with a secondary task. This increase is descriptively the highest on the lowest drowsiness level (level 1) but lasts until level 4. With secondary task (HA+QT) there is again only a slight increase in state 1, which might have the same reason as in the MAN condition. For the following drowsiness levels (especially on level 3 and 4) the interaction with the secondary task seems to have a remarkable “awakening-effect”.

Furthermore, in order to analyze the effects of the take-over scenario and the transition back towards manual driving, the last section in the test phase (just before TOR, “end” in figure 2b) and the first section after the TOR scenario (“after”) are compared. Only in the HA condition there is a clear shift towards an increased alertness. Obviously the drivers got out of the loop caused by the monotony and are brought back into the loop by the take-over request. This “awakening effect” cannot be identified in the HA+QT condition as the drivers did not reach that high drowsiness levels anyway during the test phase. Therefore it gets much more unlikely that the TOR might have an additional effect on that. In the MAN condition this “awakening” effect is not as marked as in the HA condition, because the driver stayed more in the loop before so that the effect was minimized. Another explanation could be that drivers did not perceive a kind of preparation to the situation as it had been the case in the HA condition where a take-over request had been given visually and acoustically 12 seconds before the scenario. Therefore it cannot be excluded that the HMI design itself created the awakening effect rather than the situation itself. Furthermore the section, called “after” refers only to a 1 minute section not allowing the conclusion on a long lasting awakening effect. Anyways all test-drivers took over the driving task in time and showed the ability to safely get around the construction site.

5. Conclusions

The presented study investigated the effects of highly automated driving on driver’s drowsiness development. Due to the state-dependent experimental plan it was possible to assess the effects of initial drowsiness level on the further development of drowsiness when a HA system had been activated and used for 15 minutes.

Due to the varying number of valid cases per cell the data were only analysed in a descriptive non-statistical way. Nevertheless, the results show that the increase in drowsiness was highest when drivers proceeded driving manually and when driving highly automated without having the opportunity to interact with another non-driving related activity inside the vehicle.

However, during the interaction with a moderately demanding quiz task the drowsiness level stayed on a relatively low level. In this condition the activation of the HA system together with the opportunity to direct one’s attention to the quiz task resulted in the largest awakening effect compared to the other two conditions. It can be concluded that an interesting and motivating activity which is offered the driver during a highly automated drive has the potential to raise driver’s alertness to an extent that a massive increase in drowsiness during the activity can be prevented. Due to the setup of the study, this effect could only be proven for the duration of the test phase as long as

the activity was performed. As the end of the highly automated drive was always connected with the take-over request which in itself acted as an “alerter” the prolongation of the activating effect of the quiz task could not be verified.

In addition to the results presented in this paper, also the take-over ability of the drivers was analysed. The results give hints that a take-over request 12 seconds before a system limit is reached was long enough that even on the highest drowsiness level drivers could solve the situation without any meaningful performance impairments.

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